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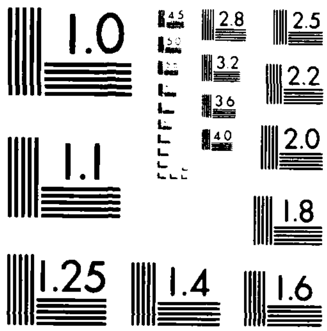
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THE IMAGING OF INTERNAL WAVES BY THE SEASAT-A SYNTHETIC APERTURE RADAR

by

MT BAGG

KI JOHNSON

ADMIRALTY RESEARCH ESTABLISHMENT
PORTLAND

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THE IMAGING OF INTERNAL WAVES BY THE SEASAT-A SYNTHETIC APERTURE RADAR

ABSTRACT

1. This paper presents results derived from a study of some 5 million square kilometres of optical survey processed SEASAT-SAR imagery of the Northeast Atlantic. In the study, markings attributed to internal wave activity were collated on maps together with the relevant bathymetry and surface meteorology. Two thirds of the imagery shows some evidence of such activity. The markings occur extensively at locations from Iceland to the Azores. Simple analysis techniques have been applied systematically to compare the very large data sets involved. In addition to the imaging of internal waves in the area covered the characteristics of the internal wave features are discussed. Finally, a small portion of the imagery, of the region between Scotland and Iceland, is studied and discussed in greater detail as a case study.

INTRODUCTION

2. The SEASAT-A satellite was launched on 26 June 1978. It carried a suite of microwave instruments and was the first satellite to be designed primarily for oceanographic research. The design was for a one-year operating period but a major power failure occurred on 10 October 1978, after 107 days, which ended the mission. The most important and useful instrument on SEASAT was the Synthetic Aperture Radar (SAR), the first such radar to be launched into space. The SAR system is described by Thompson and Laderman (Ref 18) and is the instrument with which this report is concerned. The imagery of the Northeast Atlantic Ocean used here was recorded during August and September 1978 at the Royal Aircraft Establishment's Oakhanger ground station.

3. One of the most unexpected aspects of the SAR imagery of the Northeast Atlantic is the number and extent of surface features believed to be due to internal wave activity. The imagery has been considered as a synoptic picture and a qualitative study conducted of the circumstances under which such features were imaged. The characteristics of the features are also considered. The only analysis techniques employed are those capable of being applied to large data sets without the need for computer image processing. These simple techniques have been applied systematically and it is shown that they can, in fact, provide a significant amount of information.

4. Before the main work is presented a brief summary of the basic principles and history of internal wave remote sensing is given.

CONCLUSIONS

5. This study has used the large amount of SEASAT-SAR imagery of the Northeast Atlantic which is available in optical survey processed form. This imagery has been analysed in a qualitative manner and considered together with supporting meteorological and bathymetric information. The techniques used have been applied both systematically and conscientiously and it is believed that several conclusions can be drawn.

6. When considering the whole image set:

a. Internal wave surface features can be imaged in water depths ranging from less than 50m to greater than 5,000m.

b. These features can also be imaged with surface winds ranging from 2 m/s to in excess of 15 m/s.

c. The likelihood of imaging internal waves decreases with increasing water depth and wind speed.

7. When considering the case study of passes 719 and 762, ascending from Scotland to Iceland:

a. A large number of separate internal wave features (53) are seen in the area imaged, which is one of complicated bathymetry (average depth 500m) influenced by moderately strong ocean currents.

b. The predominant internal wave propagation directions oppose the currents, probably due to the features being generated as internal lee-waves which are shed by tidal modulation of the current.

c. Under favourable conditions changes in water depth appear as important as absolute depth for identifying areas of the highest observed activity.

d. Internal wave source zones could be located by the identification of feature types and the consideration of feature propagation direction.

INTERNAL WAVE SURFACE EFFECTS

8. Internal waves exist in the body of the ocean, propagating in stratified regions of the water column where the local vertical gradient of density allows natural oscillations at frequencies higher than that of the internal wave. The highest oscillation frequency supportable by the water column at any point is called the Brunt-Väisälä frequency. In regions of mixed water, internal waves cannot exist as real waves. The typical structure of the open ocean tends to define horizontal layers within which internal waves exist. No waves are present within the surface mixed layer. Below this, high frequency waves, of up to 20 cycles per hour exist in the vicinity of any strong seasonal thermocline, while lower frequency waves, of up to 4 cycles per hour, are found from the base of the surface layer down through the permanent thermocline.

9. In order for the internal waves to be remotely sensed there must be a mechanism by which some wave energy can reach the sea surface and, once there, cause a measurable disturbance. When the thermocline effectively reaches the surface, internal waves can propagate right up to the surface. In other cases, when an appreciable mixed layer exists, energy reaches the surface through the evanescent mode of the internal wave. The length scale of the evanescent energy decay is the depth of the mixed layer divided by the internal wavelength. Typical conditions in the ocean potentially allow significant amounts of energy to arrive at the surface. This energy is in the form of horizontal currents, with the change in surface height being negligible. The currents produced above the internal waves can modify the short scale sea surface roughness. This is either directly by interacting with the capillary and short gravity waves or indirectly by gathering natural surface oils into bands, which in turn modify the wave pattern.

10. The modifications of sea surface waves due to internal wave induced surface currents have been studied theoretically and experimentally for at least the last ten years. Two notable pieces of work in this field are Lewis et al (Ref 14) and Hughes and Grant (Refs 11 and 12). These papers show that short surface gravity waves have their slope and amplitude perturbed over a lengthscale characteristic of the internal wavelength. Apel and Holbrook (Ref 4) show that the surface roughness overlying coherent internal waves bears a definite phase relationship to the underlying internal wavefield. In particular, rough surface regions appear to be phase-locked to the downgoing (trough) phases of the internal oscillations; these being followed by anomalously smooth surface bands. The surface wavelengths which suffer the greatest modification are of the order of centimetres.

11. Modifications of the short scale surface roughness have been investigated by many workers with a view to exploiting the effects to derive parameters of the sea surface. Cox and Munk (Ref 6) show that glitter patterns due to roughness variations affecting the specular reflection of sunlight can be used to detect small sea surface slopes. In the optical case the illumination/viewing geometry is critical. More recently Gower (Ref 10) and Tomiyasu (Ref 19) amongst others have shown that SAR is a very good, and potentially a very reliable, detector of sea surface roughness variations. Internal waves are capable, under some circumstances, of causing modifications of the sea surface which are detectable by airborne and spaceborne SAR (Ref 16).

REMOTE OBSERVATIONS OF INTERNAL WAVES

12. Many workers have reported observing the effects of internal waves on aircraft or satellite imagery, sometimes with simultaneous in-water measurements but often without. A major problem is the different nature of the two types of observation; shipborne measurements are often temporal while the remote measurements are spatial. Simultaneous measurements are usually only achieved when specific experiments are organised on a necessarily large scale.

13. The first internal wave features to be identified from space were patterns in sun glitter off the north-east coast of the USA. These were seen on optical imagery from the Earth Resources Technology Satellite (renamed LANDSAT) and were confirmed as being associated with internal waves by near-simultaneous shipborne measurements (Refs 1,2,3). Other similar sun glitter patterns have been reported from various parts of the world on imagery from the LANDSAT satellite series. An atlas of the patterns observed around the United States has been compiled by Sawyer and Apel (Ref 17).

14. SAR, being an active, all-weather system, has far greater potential than optical sensors for internal wave monitoring and much effort has been put into studying it. Before a SAR had been launched into space on SEASAT, aircraft systems had been used in experiments. The Jet Propulsion Laboratory's L-band (23 cm) system was used to image internal wave features off the Oregon coast (Ref 7). The same system was used to image similar features further north, off British Columbia, by Canadian workers (Ref 10). Measurements of this latter area, around Vancouver, were made using the Canadian SAR-580 aircraft system (Ref 13). Here a ship was used to generate internal waves on the shallow interface between fresh river and saline ocean water which occurs in the area. The ship measured the wavefield generated for comparison with airborne optical and radar images and also with imagery from the SEASAT SAR. The remote and in-water measurements were found to be in very good agreement.

15. There have been two spaceborne SAR systems to date, on the SEASAT satellite and second Space Shuttle mission. Many workers have commented upon the ability of these to detect internal wave surface effects. Reviews of the radars' performance (Refs 8, 20) make reference to, and give examples of, the imaging of these effects. Probably the most comprehensive study of the SEASAT imagery of internal waves to date is that of Apel and Gonzalez (Ref 5). They consider a large number of features seen in a single image off the west coast of Baja California. Parameters of the observed packets are derived. In addition models, based on linear and non-linear theories of internal wave propagation, are worked to make predictions of the appearance of these packets when measured with in-water instruments.

STUDY OF THE FULL IMAGE SET

Analysis Technique

16. The source material used throughout the study now reported was standard optical survey-processed negative transparency film. This was produced by ERIM from the Oakhanger records. There were 73 image sequences of the Atlantic derived from 30 of the 53 SAR passes recorded at Oakhanger. This comprised 5 million km^2 of sea surface and was the basic data studied. Each image swath was plotted onto a map using information supplied by the European Space Agency's ESRIN/Earthnet Office (Ref 9).

17. The imagery was surveyed for internal wave features by eye with the aid of a light box and graduated eye glass. This allowed some length scaling of the observed features. Such features were classified according to characteristics reported in the references. Three types of feature, thought to reveal the presence of internal waves, were observed. The most common of these were "wave packets". They showed a degree of wavefront curvature and decreasing wave and crest length from front to rear giving the impression of being a V-shaped sector of Huyghens wave group radiating from a point source. The lines of sea surface modulation are well defined and narrow compared with the wavelength. The second type of feature was recorded as "slicks". These were seen as less well defined lines of modulation occurring with large spacing in long parallel groups, but without obvious packet structure. A very few observations were made of isolated, well defined single lines of internal wave character; these were recorded as "single waves".

18. The location of each feature seen was plotted onto the swath maps. The accuracy of location was between about 5 and 25 kilometres, depending upon the presence and proximity of land for cross-checking. The number of internal wave features seen was so great that counting and locating them individually was not possible. Instead, an observation was recorded when either a lone feature or a small, apparently related group of features was seen. Features seen at the same location but which appeared unrelated were recorded as separate observations.

19. In addition to the location and character being recorded a subjective judgement of the clarity of each feature against the image background was made. Each observation was classified as being distinctly, intermediately or faintly visible.

20. Once all the internal waves had been plotted bathymetric and meteorological conditions were added. With the bathymetry added, it was evident that features were imaged in a great range of water depths. Each observation was, therefore, classified as occurring in shallow water, of less than 600m; medium water, from 600m to 1500m; or deep water, of deeper than 1500m. The surface meteorology at the time of imaging was derived from the twice daily synoptic charts of the North Atlantic. The surface analysis closest in time to each image pass was drawn on the swath maps, along with actual wind speed and direction observations. Under stable conditions the winds shown were taken to be those present at the time of imaging but in more mobile circulations two or three charts were used to judge the winds at the imaging time. Each observation was classified as occurring under low; up to 10 knots, moderate; 11 to 20 knots, or high; 21 knots and above, surface winds.

21. In order that the geographic distribution of all the internal waves imaged might be studied the observations were plotted on a single map, gridded in 2 degree squares. Many features were of such a size that they fell in more than one square in which case each square was considered to contain an observation. To allow any results to be normalised it was necessary to consider the total occurrences of each wind speed and water depth class and also the number of times each grid square was covered for the full set of imagery studied.

RESULTS

Geographic location

22. A total of 128 observations of internal wave surface features was recorded from the imagery studied; of these 112 (88%) were wave packets, 12 (9%) slicks and 3 (3%) single waves. Figure 1 has been produced by dividing the number of

observations made in each 2 degree grid square by the number of times that square was imaged and indicates an observation frequency for internal waves in each square. Blank squares indicate areas where there was no coverage and squares containing a zero represent those imaged where internal waves were not observed. It can be seen that observations were made throughout most of the area imaged.

23. The areas observed to have the highest internal wave activity are regions of relatively shallow water. The largest of these is around the north and west coasts of Scotland, over the continental shelf. To the west activity is lower over the Rockall Trough but rises again at the Rockall Bank. In the north there is high activity around the Faeroe Islands and the southeast coast of Iceland. The remaining region of high activity is to the northeast of the Azores, above the eastern edge of the Mid-Atlantic Ridge. The lowest activities were seen in deep water areas where there is little significant bathymetry.

Feature characteristics

24. The observed features seemed, subjectively, to fall into three geographic groups. In the coastal regions of Iceland, Scotland and Ireland very small wave packets were most common. These were well defined with sharp boundaries, often occurring in small groups. The leading wavefront lengths of the packets ranged from 1½ to 5 kilometres with a decrease in length at the rear of the packet giving a definite V-shape to the packet. Up to 10 waves could be identified in a packet, with a wavelength range of 120 to 400 metres.

25. In the deeper water of the northern half of the imaged region the majority of the features were much larger, but still well defined packets. Here the leading wavefront lengths ranged from 10 to 72 kilometres. These packets had only slight curvature and a less obvious V-shape. Typically 5 waves were seen in a packet with wavelengths from 300 metres to 2½ kilometres. The propagation direction could often be deduced and was commonly from west to east.

26. To the south of about 50°N the features changed in character and had much less definite boundaries. The internal waves here appeared to be less well ordered and propagation directions variable. The dimensions of the wave packets seen were comparable with the deep water packets in the north but they had greater wavefront curvature. The blurred appearance of these features on the imagery made their measurement difficult. All of the recorded slick features were recorded in this southern region.

Water depth and wind speed

27. The imagery studied coincided with a wide range of water depths and wind speeds. Regarding water depth, 26% of the imagery was of shallow water, 38% medium and 36% deep water. Surface wind speed had a similar spread with 25% of the imagery coincident with low winds, 41% moderate and 34% high winds. These figures have been used for normalisation of the observations. Table 1 shows, before normalisation, the number of observations in each water depth and wind speed class.

		Wind Speed			
		Low	Moderate	High	Total
Water Depth	Shallow	18	20	10	48
	Medium	30	15	5	50
	Deep	27	3	0	30
	Total	75	38	15	128

TABLE 1. The number of observations in each water depth and wind speed class.

28. Figure 2 shows the normalised observations in each water depth regime. It can be seen that packet features were most often seen in shallow water and least often in deep water; a result drawn from 112 observations. The shallowest observation was in less than 50m of water and the deepest in excess of 5000m. Slick features were mainly seen in deep water; a result, though, drawn from only 12 observations.

29. Figure 3 shows the relationship of the observations to wind speed, for all observations, and also for those in each water depth class. Over two thirds of all observations coincided with winds of 10 knots and less and a tenth with winds in excess of 20 knots. Two features were judged to have been imaged when the wind was greater than 30 knots. When the observations in each water depth class are considered separately internal waves can be seen to be imaged most often under light winds in each case. In shallow water, however, the chance of making an observation decreases only gradually with increasing wind speed. As the water depth increases so does the rate of fall-off of observations. It would appear that as the water depth increases, increasing wind speed is more likely to mask or destroy the internal wave surface features.

Clarity

30. Although the determination of feature clarity was highly subjective, figure 4 would appear to show a significant result. Nearly half of the observations in shallow water were recorded as being distinct whereas over half of those in deep water were faint. Those in medium depth water exhibited an even spread of clarities.

31. This result suggests that the internal wave surface effects, on average, increase in strength as the water depth decreases.

DISCUSSION

32. These results, taken together with a recent study (Ref 16) provide a possible insight into the internal wavefield in the upper layers of, at least, the Northeast Atlantic. The imagery suggests that in the surface waters the internal waves are neither horizontally isotropic nor statistically stationary, but have directionality and occur in bursts with relatively quiet conditions between them. It is thought that features associated with two types of internal wave are being seen; some are being generated in shallow water and being imaged close to their source while others are generated in deeper waters and, in some cases, propagating long distances before being imaged. The first group are wave packets generated by tidal or current flow across the

continental slope and similar bathymetric features. These are considered to be similar to previously reported shallow water internal waves (Refs 2, 3). The latter set of features is thought to result from solitons, similar to those observed in the Andaman Sea (Ref 15).

33. Many of the features seen in deep water appear to be propagating from west to east. These could well be generated at the Mid-Atlantic Ridge, in the permanent thermocline, by bottom currents. Initially a disturbance here would be a local raising of the density surface, which would evolve into a group of solitons with a tail of "linear" waves. Such solitons could propagate over large distances and, with the permanent thermocline being reasonably isotropic, suffer little attenuation whilst in deep water. In time the wave energy will spread throughout the considerable depth range over which the density structure can support it. The energy density in deep water is, therefore, likely to be small. As the water depth decreases, the energy density is likely to increase, until the solitons are upon the continental shelf where the energy will be dissipated. It is probable that the strength of the surface effects leading to internal wave imaging is related to the energy density which would explain why internal waves are seen less frequently, more faintly and with a much more severe wind speed constraint in deep water as compared with shallow water.

FEATURE CHARACTERISTICS

34. Following the survey of the large amount of SEASAT-SAR imagery available off the Northeast Atlantic it is possible to describe in more detail the characteristics of the internal wave features. It appears that these features can be classified, by their characteristics, into a small number of groups. The size and shape of a feature could also provide some indication of its age.

35. On the imagery the internal waves appear either as narrow dark bands, of reduced sea surface roughness, or as adjacent narrow light and dark bands. These bands are seen against the general grey background of the sea return. The bands often occur in groups, separated by the internal wavelength. The spacing between them is often greater than bandwidths. The bands most probably lie above the internal wave troughs. This would be consistent with the inverse cnoidal waveform in Robinson et al, (Ref 16). The bands observed are generally about 100m wide, with wavelengths ranging from 120m to 2.2 km, and from a few kilometres to over 70 km long. Occasionally long, wider dark bands with rather diffuse edges are imaged. These have wide spacing and are only seen under ideal imaging conditions.

36. The features can be divided into four classes, two of these with sub-groups giving seven feature types. The characteristics of each type are described below. It is thought that all of these features can be regarded in terms of dispersive Huyghens wave packets. This is illustrated in the sketches shown in Figure 5. The feature types are:

Types a and b: Young and Old Curved Packets

37. This class contains the features with the smallest dimensions seen on the imagery. They are observed as packets of from four to ten waves. The lines of surface modulation (wavefronts) are continuously curved with the longest wavefront on the convex side of the packet (presumed to be leading) and the shortest at the "rear". The apparent wavelength also decreases from front to rear.

38. The smallest packets have a leading wavefront length of only a few kilometres and wavelengths ranging from just over 100m (the shortest which could be imaged by the radar) to 300m or so. The wavefronts have a high degree of curvature with the packet having an (apparent) sector angle of some 60°. The largest packets in this class still show definite curvature along the whole length of their wavefronts. Their sector angle is less than 30° and their dimensions 3 to 4 times larger than the smallest packets. The distance of a packet from its "source" gives the impression of being proportional to its size. In most cases the lines of surface roughness modulation appear to have very sharp edge boundaries. Figures 5a and 5b show "young" and "old" curved packets propagating away from an apparently local point generation source. These features are often seen to occur in parallel lines with up to four being formed side-by-side, with a further one or two similar lines of pockets behind.

Types c, d and e: Young, Developed and Old Straight Packets

39. This class of features is similar in many ways to the curved packet class, and can be regarded as a continuation of it. The distinguishing characteristic of packets in this class is that most of each wavefront is straight, some having slightly curved ends. Again the longest wavefront "leads" the packet, and the shortest trails and the wavefronts have reasonably sharp edges. Wavefront lengths can vary from 10 km to over 70 km and wavelengths from a few hundred metres to over 2 km. On average five wavefronts are imaged in each packet.

40. Some of the packets in this class show marked dispersion with the wavelength of the first wave being twice that of the last. The wavefronts in these packets have both dark and light components. Other packers show only a small degree of dispersion and have only a light, reduced surface roughness, component in the wavefront. The orientation of wavefronts within a packet is very uniform.

41. As the curved packets evolve they can merge into one another, both from side-to-side and, being dispersive, from front to back. These evolved features are called straight packets and are classified in three sub-groups, shown in Figures 5c, 5d and 5e. The youngest show dispersion and a small degree of curvature, developed packets have no curvature but still some dispersion and the oldest have neither curvature nor dispersion.

Tye f: Slicks

42. Slicks are distinct in character from the other three classes of feature and they comprise some 10% of all observations. On the imagery they are seen as light bands several tens of kilometres long, often with three or four lying parallel, each band being up to 400m wide with two to four kilometre spacings. In contrast with other features the slick surface modulations appear to have "ragged" edges with the width of each feature being hard to determine. This "raggedness" is the main distinguishing characteristic of slicks. These features have mainly been imaged in deep water at low wind speeds. Some are seen in regions of apparently high internal wave activity but most as isolated features in an otherwise uniform portion of image.

43. In time, internal wave packets generated at the same location at different times (perhaps one tidal cycle apart) could merge to become indistinguishable. As they evolve, the surface effects of the packets will become weaker. At the time of imaging a number of pairs of waves could be nearly matched, accounting for the observed slick features as in Figure 5g. The reinforcement mechanism could account for the diffuse nature of the feature, the sensitivity to wind speed and their appearance in otherwise featureless, open, deep ocean areas.

Type g: Single waves

44. Single waves are the rarest feature seen on the imagery. In appearance they are very much like a single wavefront from a "straight packet". Those seen are about 50 km long and generally straight, but with a few gentle kinks. They are put in a separate class, rather than being a "one wave packet", as their appearance suggests that there should be other components with it. The single waves occurred in otherwise featureless areas of imagery covering deep water away from land.

45. Single waves could be imaged when a slow wave of one packet is exactly caught and matched by a faster wave of a later packet, producing a single strong surface effect (Figure 5g). This mechanism would account for the rarity of single waves.

A CASE STUDY - PASSES 719 AND 762

46. In the descriptions of the SEASAT-SAR imagery given above the whole of the available imagery (some 5 million square kilometres) has been used. For this case study only a small portion of imagery, two passes between Scotland and Iceland, is used. This allows the imagery to be viewed in much greater detail. In addition to identifying and locating all the internal wave features on the imagery it appears that a careful cataloguing of features could provide an empirical technique for the identification of internal wave source regions.

Analysis technique and results

47. Four image sequences were used, numbers 4 and 5 from passes 719 and 762, which follow nearly identical ascending swaths from Scotland to Iceland. Pass 719 was at 0640 GMT on 16 August. At this time the region was experiencing light to moderate north westerly surface winds. A ridge of high pressure was approaching from the west, behind a shallow depression. The winds were strongest near Iceland. A vigorous depression passed through the region after the ridge and was just clearing the imaged area at the time of pass 762, 0646 GMT on 19 August. At this time the winds were fresh to strong from the south south-west.

48. As in the previous studies the image sequences were viewed with the aid of a light box and graduated eye-glass. This time, however, each internal wave feature was identified and noted separately, rather than in groups of similar type. In all, 53 features were identified; the locations of these being shown in Figure 6 (numbers 1 to 33 being from pass 719 and numbers 34 to 53 from pass 762). The limits of the imaged region are also shown. As each feature was noted it was classified as one of the seven feature types shown in Figures 5a to 5g. This classification is, to an extent, subjective as individual features often do not conform exactly to the generalised descriptions. Often the biggest problem is deciding between the sub-groups of the straight packet class.

49. Figure 7 shows again the locations of the observed features, this time, however, coded by feature type. Figure 8 shows the direction of propagation deduced for each feature; in all cases this is the direction in which the internal waves are assumed to be advancing. The catalogue of observations is summarised in Tables 2 to 4. Table 2 shows the relationship between feature type and the deduced directions of propagation, Table 3 shows the observed clarities of each feature type and Table 4 shows the observed clarities of features propagating in each direction.

Propagation Direction (towards)	Feature Type							
	a	b	c	d	e	f	g	TOTAL
North	-	-	-	-	-	1	-	1
North-East	-	3	1	1	-	-	3	8
East	-	-	-	-	-	-	-	-
South-East	2	1	1	-	-	-	-	4
South	-	-	1	4	-	-	-	5
South-West	3	9	8	5	-	2	-	27
West	-	2	-	-	-	-	-	2
North-West	3	1	1	-	1	-	-	5
TOTAL	8	16	12	10	1	3	3	53

TABLE 2. The Relationship between Feature Type and Propagation Direction.

Clarity	Feature Type							
	a	b	c	d	e	f	g	TOTAL
Faint	1	6	4	5	-	1	-	17
Average	3	7	5	5	1	2	2	25
Distinct	4	3	3	-	-	-	1	11
TOTAL	8	16	12	10	1	3	3	53

TABLE 3. The Observed Clarities of Each Feature Type.

Clarity	Propagation Direction								
	N	NE	E	SE	S	SW	W	NW	TOTAL
Faint	1	3	-	2	3	6	-	2	17
Average	-	3	-	1	1	15	2	3	25
Distinct	-	2	-	1	1	6	-	1	11
TOTAL	1	8	0	4	5	27	2	6	53

TABLE 4. The Relationship between Observed Clarity and Propagation Direction.

Discussion

50. The image swaths from the two passes considered lie along the western edge of the ridge system between Scotland and Iceland. The water depth is generally between 400m and 700m but decreases to less than 100m close to Scotland, Iceland and the Faeroes. Internal wave features are observed along the whole length of the region with the majority in the southern half, over the Scottish continental slope and the Wyville-Thompson Ridge. This southern region has the most complicated bathymetry. It would appear that changes in water depth are as important as absolute water depth for the imaging of internal waves under favourable conditions. Figure 7 suggests that sea-bed troughs and canyons are significant topographical causes of internal wave generation. Looking also at the different feature types suggests, perhaps with a little imagination, that "young" features occur in small groups with "older" features appearing progressively further away.

51. Two ocean currents influence the area. The North Atlantic Drift flows north-east, strongly between Scotland and the Faeroes with a weaker flow to the north of the Faeroes; the Southeast Iceland current counters this, flowing south-west along the Icelandic coast. Two-thirds of all the observed features are deduced to be propagating against these currents, the change from south westerly propagation to north-easterly on approaching the Iclandic coast being very noticeable.

52. Superimposed upon this apparent favouring of propagation against the current there seems, in the southern area, to be evidence of features propagating radially away from source zones. The source zones so identified are the same as those found by considering the apparent "age" of each feature.

53. It is generally believed that the mechanisms by which the SAR images internal waves favours the imaging of range travelling waves, although these mechanisms are not yet well understood. This could account for the predominance of features observed to be travelling south-west/north-east. Features with this orientation, however, are not seen any more clearly on the imagery than any of the others. It is most likely that propagation against the current is the dominant factor. Should this be so, the generation of the internal waves is probably through internal lee-waves formed at depth by the flow of the current over the ridge/trough formations of the area. Some event, such as tidal modulation of the current, would cause these waves to be shed and propagated away, as the features seen, against the current.

54. The most often seen feature types are b and c with types a and d less frequently and the "older" types only infrequently, in this area. Generally the "younger" types are seen more clearly than the "older" ones. The area covered by the imagery, however, is one of relatively shallow and complicated bathymetry where internal wave generation could well be expected. This would lead to the quantity and clarity of "young" features which is observed. The results from a more open region well to the west of Europe would likely be very different.

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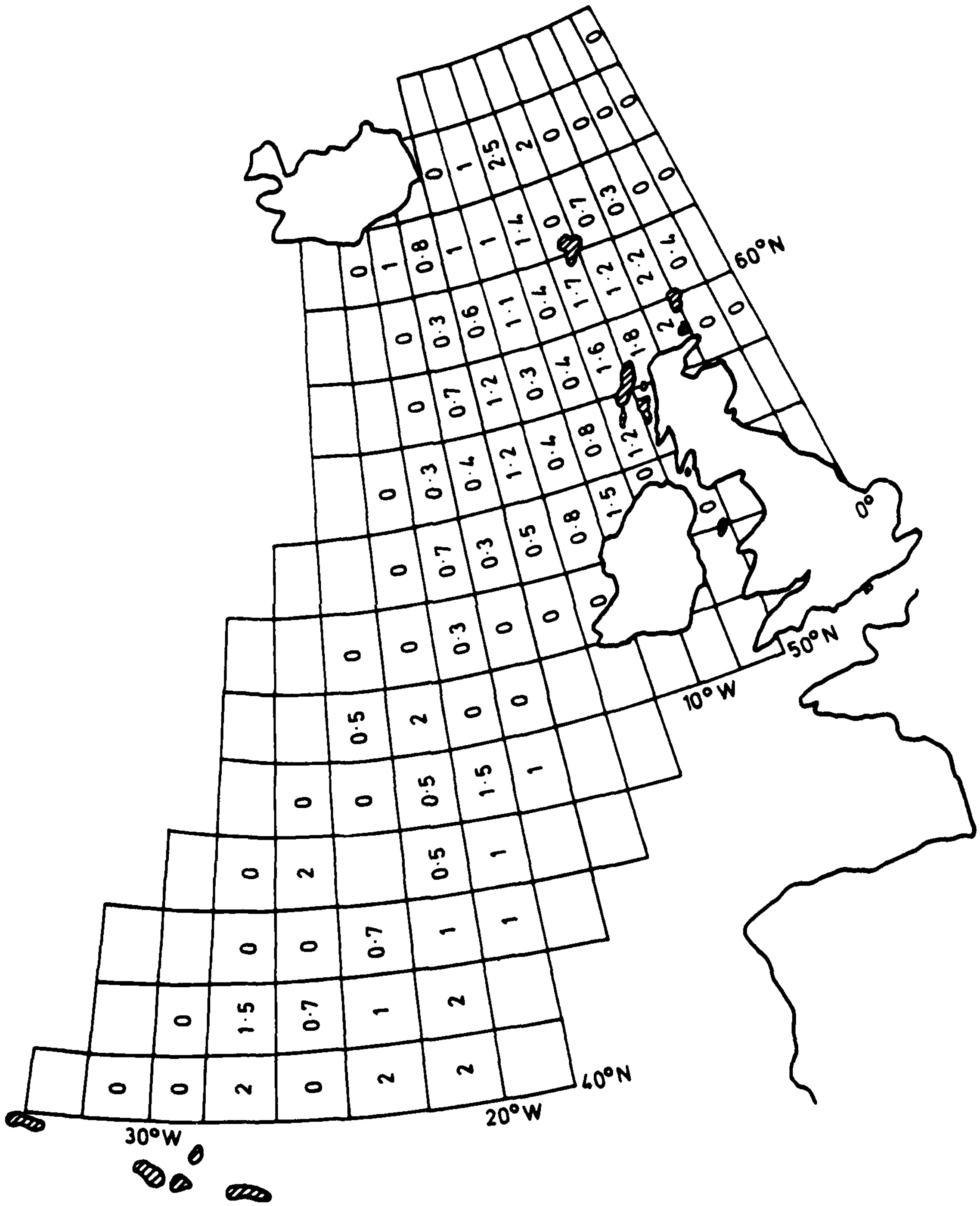

FIGURE 1: INTERNAL WAVE OBSERVATION FREQUENCY
BY 2 DEGREE SQUARE

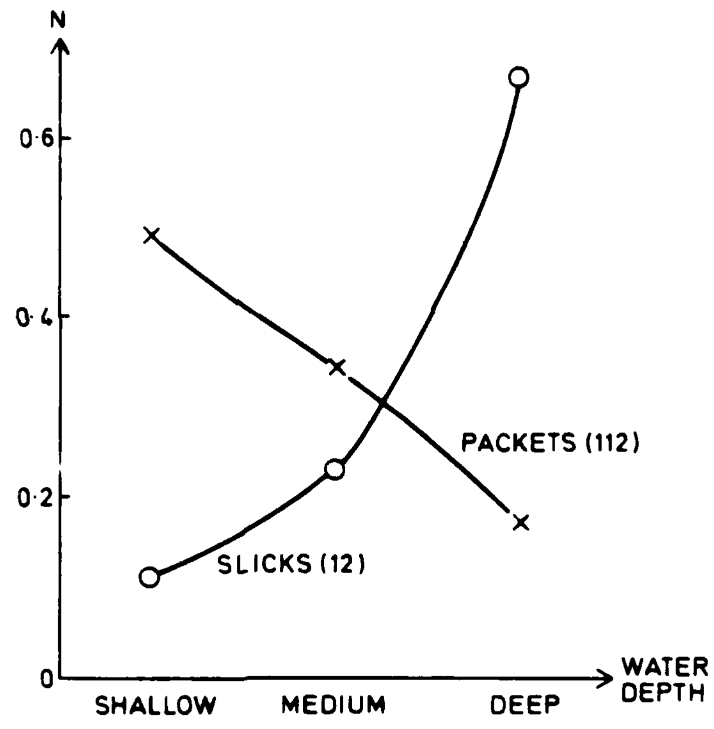

FIGURE 2: RELATIONSHIP OF OBSERVATIONS TO WATER DEPTH

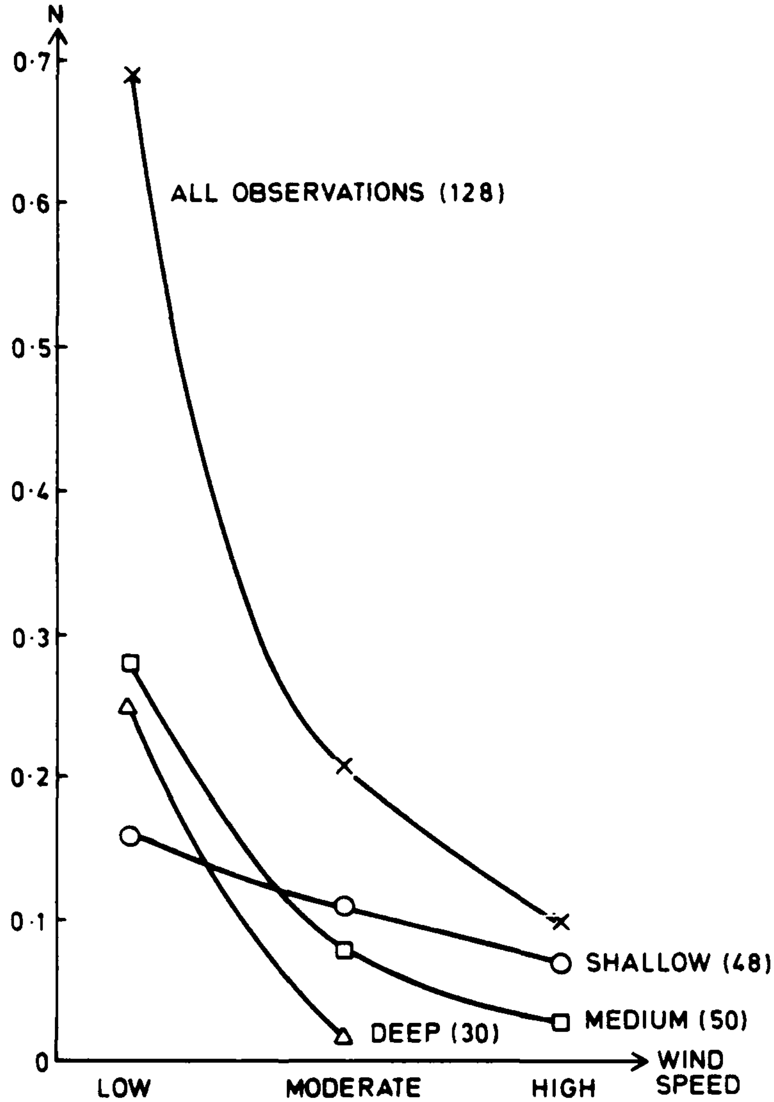

FIGURE 3: RELATIONSHIP OF OBSERVATIONS TO WIND SPEED

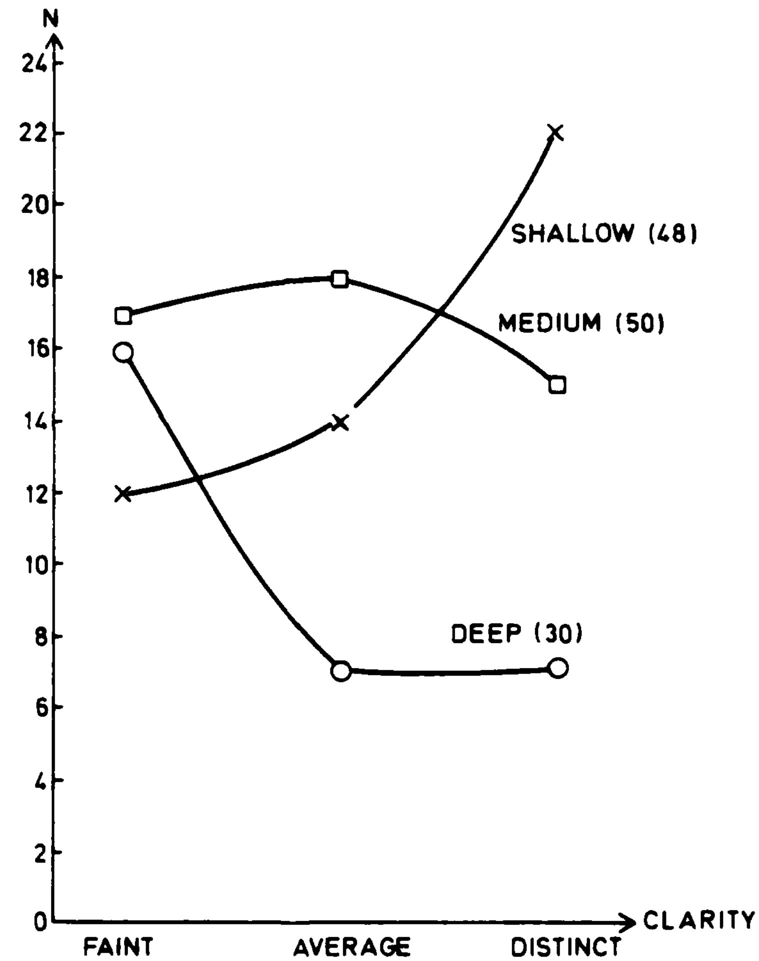

FIGURE 4: CLARITY OF OBSERVATIONS IN EACH WATER DEPTH CLASS

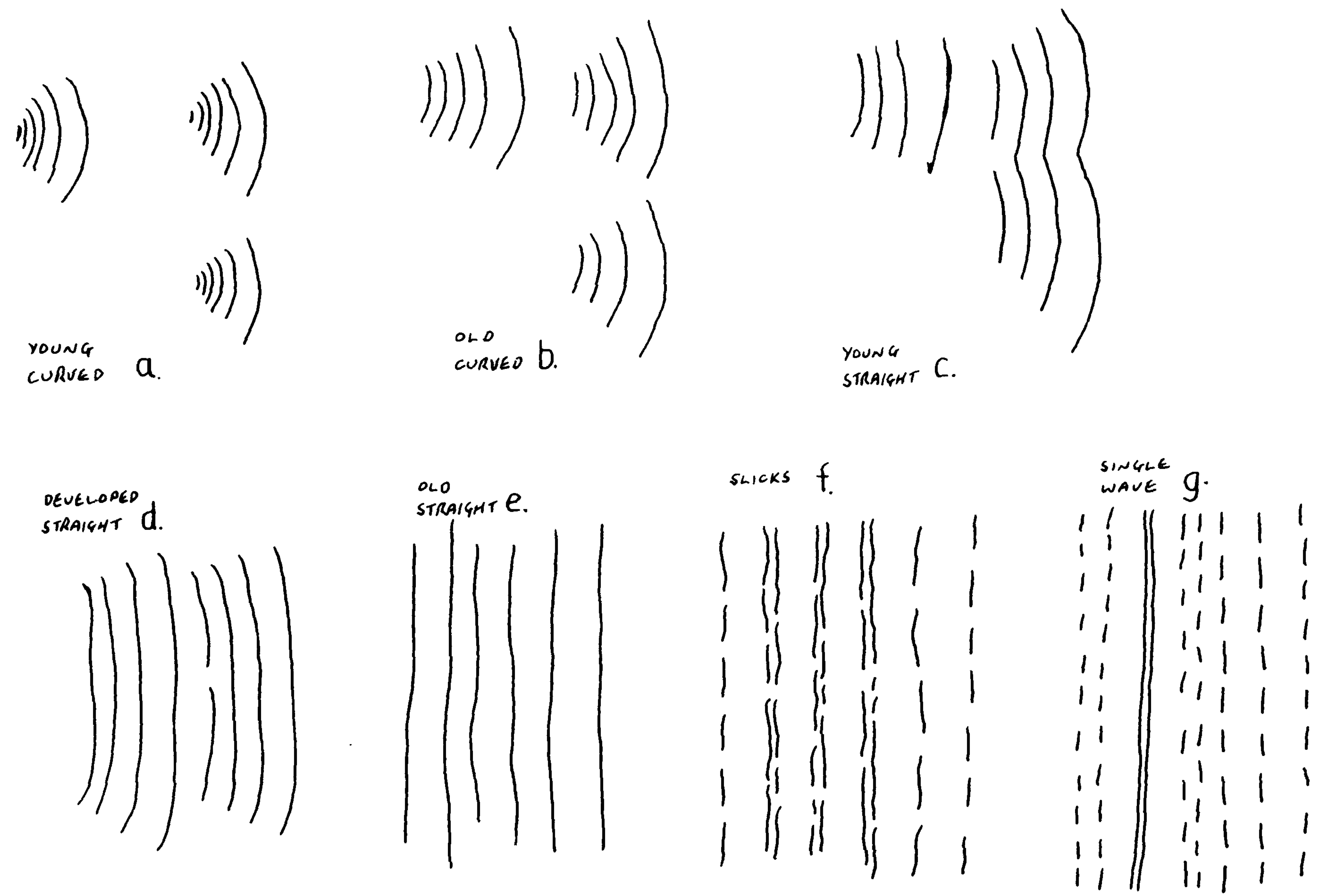

FIGURE 5: INTERNAL WAVE FEATURE TYPES

FIGURE 6 LOCATIONS OF INTERNAL WAVE FEATURES ON PASSES 719 AND 762

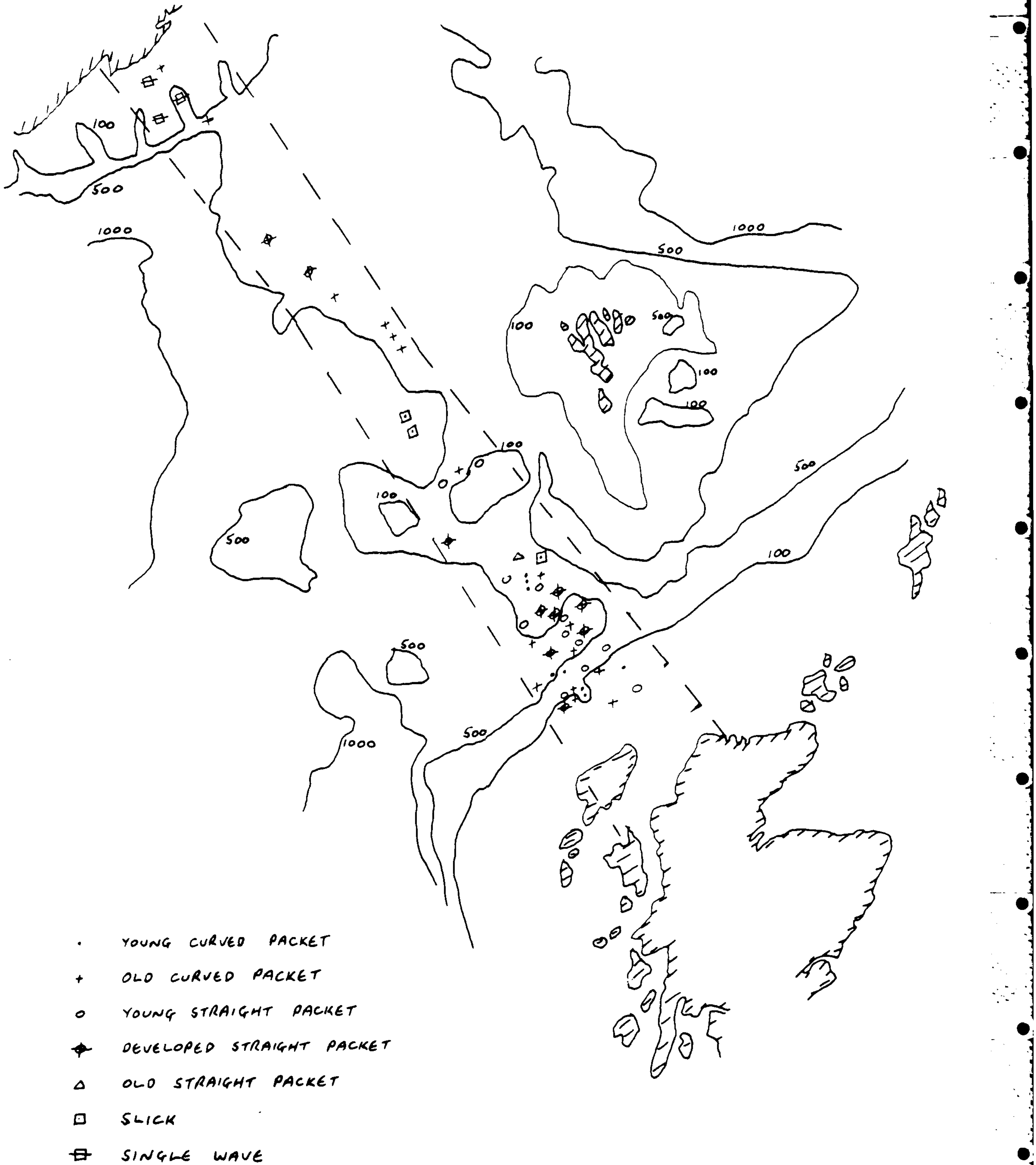

FIGURE 7. INTERNAL WAVE FEATURES OBSERVED ON SEASAT-SAR PASSES 719 AND 762 - LOCATIONS BY FEATURE TYPE

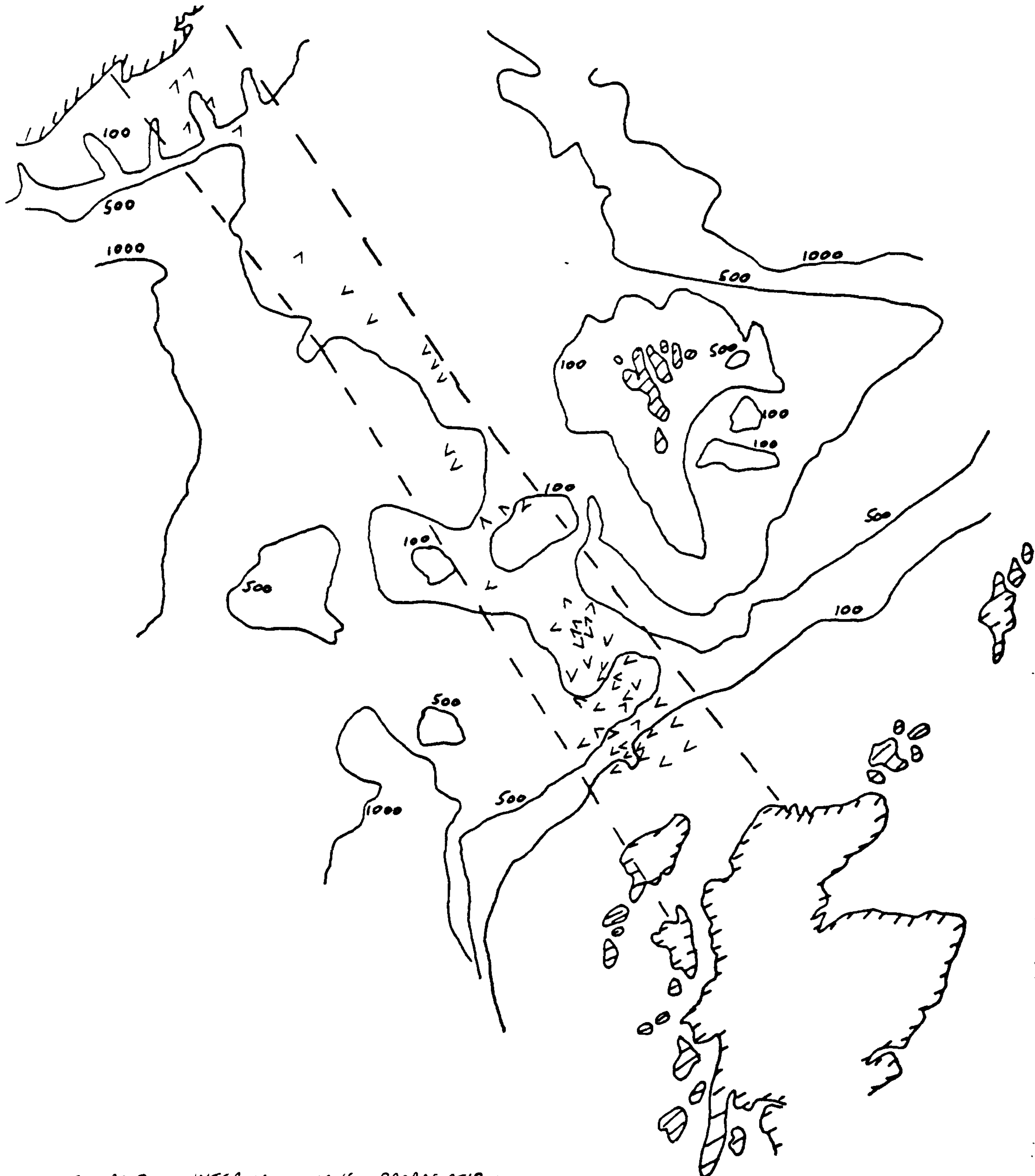

FIGURE 8 INTERNAL WAVE PROPAGATION DIRECTIONS
PASSES 719 AND 762

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Abstract

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